MICROMEMBRANE ACTUATOR

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0001] This invention relates to a compact actuator that utilizes small thin shape memory alloy (SMA) diaphragms to provide large force output at high drive frequency. The actuation is based on a shape memory alloy miniature pump, which rectifies liquid to achieve stroke for the actuator. A bias pressure is applied to bend the SMA membrane upward to form a cavity between the membrane and a surface in the actuator body upon which the unbiased membrane sits. A pulse of charge is used as resistive heating so that membrane accomplishes a plunging stroke towards the surface when heated, thereby forcing liquid out of the cavity. High drive frequency is reached by impinging the liquid on the heated membrane to achieve forced convective cooling. The heated liquid flows out via the outlet port. Adding additional membranes in parallel also increases the flow rate.

2. Description of Related Art

[0002] The publications and other reference materials referred to herein to describe the background of the invention and to provide additional detail regarding its practice are hereby incorporated by reference. For convenience, the references are numerically referenced and grouped in the appended bibliography.

[0003] Thin film SMA possesses unique characteristics that are attractive for use in actuators. A foremost of those characteristics is a large strain output, which can typically strain up to 8-10%. No other active materials posses this behavior, and studies have shown that fatigue life can exceed million cycles when strains are below 2% [1]. It also has the highest work densities for smart materials, for instance 25×10^6 joule/m^3 for NiTi compared to 0.1×10^6 joule/m^3 for piezoelectric materials [1]. A less well-known attribute is the thin film's high frequency response due to increased heat dissipation from large surface-to-volume ratio. While bulk SMA typically has frequency responses of less than 1Hz, thin film SMA can have frequency response on the order of 100Hz if power delivered to the thin film is carefully manipulated to

account for heat transfer issues [2]. These attributes make thin film SMA an attractive material for micro actuation devices.

[0004] Typical micro devices require large deformations while exerting sufficient forces from an actuating material. This work density is an inherent attribute of thin film SMA and has been used in SMA based micropumps. One of the first micropumps, the pumping mechanism was based on two antagonistic 3μm thick NiTi membranes [3-6]. For this pump, the push-pull pumping motions were generated by alternately heating the membranes. The pressure head generated by this motion was 519Pa while operating at drive frequency of 1Hz. At higher drive frequencies, the membranes were not sufficiently cooled thereby reducing the pumping motion and the flow rate. The maximum flow rate was 50μl/min. Therefore, this pump did not produce large flow rates or large force outputs due to the limitations of the system.

[0005] Makino and his colleagues also developed a SMA-based micropump but used a single NiTi diaphragm biased with pressurized nitrogen gas [7-10]. Their pump was able to operate at a drive frequency of 0.2Hz, which was sufficient for cooling and shape recovery of the diaphragm. Separate studies also revealed that 6μm thick NiTi diaphragms displayed larger force outputs under 500 kPa bias pressure. The flow rate was 4.8μl/min, which was achieved under bias pressure of 100kPa. This pump lacked the qualities of large force and large flow rates.

[0006] More recent development in thin film SMA micropump was based on a bimorph design where strips of 5μm thick NiTi were adhered on top of 15μm thick silicon membrane [11-14]. With this design, a 100Hz drive frequency was reported, but they also pointed out that insufficient cooling subsequently reduced diaphragm stroke causing reductions in flow rate so that this drive frequency was not sustainable. The maximum flow rate was 350μl/min at drive frequency of 60Hz.

SUMMARY OF THE INVENTION

[0007] The present invention provides a thin film SMA micro pump actuator that has high work density and high frequency response. The invention uses a miniature SMA pump to rectify liquid to achieve stroke. The invention manipulates the fluid flow to have forced convection cooling on the SMA membrane, eliminating the

insufficient cooling of prior art designs. The result is an improved design with operation at flow rates well in excess of prior art designs.

[0008] Past micropumps have not exploited the critical properties of thin film SMA which are high work density and high frequency response. The actuators of the present invention are able to achieve high output force at large velocities by exploiting both high frequency response and work density properties of thin film NiTi SMA membranes. The actuator uses a miniature SMA pump to rectify liquid to achieve stroke, which past micropumps did not consider. The insufficient cooling associated with past micropumps is also eliminated. This is achieved by manipulating the fluid flow to have forced convection cooling on the SMA membrane. By doing so, the flow rate for the current actuator increases to three times the order of magnitude higher than the past micropumps.

[0009] Additional features of the inventions are provided in the following detailed description of the preferred embodiments with reference to the drawings.

[0010] The above discussed and many other features and attendant advantages of the present invention will become better understood by reference to the detailed description when taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIG. 1 is an illustration showing assemblage of a single membrane pump actuator with SMA membrane and a retaining lid.

[0012] FIG. 2 is a cross-sectional view taken along the planes 1A—1A and 2A—2A shown in FIG 1.

[0013] FIG. 3 is a cross-sectional view of a deformed SMA membrane under bias pressure.

[0014] FIG. 4 is a front view of a pumping chamber.

[0015] FIG. 5 is perspective view of the four-membrane pump actuator formed accordance with present invention.

[0016] FIG. 6 is a perspective view of a SMA membrane that is suitable for use in pump actuators in accordance with the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0017] A pump-based compact actuator is provided in accordance with the present invention that is capable of producing a large force output and a large volume flow rate. This following detailed description sets forth exemplary embodiments that are a few of the many considered possible for this actuation system and as such this description is regarded as an example.

[0018] The actuators of the present invention utilize at least one thin shape memory alloy membrane for means of actuation. Multiple membranes may be used to increase volume flow rate. The force output of the pump can be controlled by varying the properties of the membrane, such as the thickness of the membrane. The actuator includes an actuator body that includes surfaces that define one or more actuation chambers that hold SMA membranes over a membrane seat surface that includes a liquid inlet port and multiple outlet ports. These ports are located relative to each other so that cool liquid impinges on the hot membrane for faster heat transfer through forced convection cooling. The heated liquid then flows out through an outlet port in the actuator or pump body.

[0019] The SMA membrane is heated by electrical resistive means by passing a pulse of charge through the SMA membrane. Each current pulse heats the SMA membrane thereby causing the membrane to accomplish plunging stroke, which pushes the liquid out of the chamber. The flow rate is dictated by repetition of current pulses.

[0020] In the following description, numerous details are set forth in order to provide a more thorough description of the present invention. It will be apparent, however, to one skilled in the art, that the present invention may be practiced without these specific details. In other instances, well known features have not been described in detail so as not to unnecessarily obscure the present invention.

[0021] A perspective view of an embodiment of the present invention is illustrated in FIG. 1. The actuator comprises a pumping chamber or actuator body 2a, 0-ring 4 that is preferably made from TEFLON®, inlet porthole 5, outlet portholes 6, inlet 7, and retaining lid 1 with SMA membrane 3. The actuator body includes surfaces that

define and actuation chamber in which the membrane is located. The bottom surface of the actuation chamber is a membrane seat surface as shown at 25. The 0-ring 4 provides a seal between the lid 1 and the actuator body 2a. The retaining lid 1 is pressed on to the actuator body 2a such that junctions between the TEFLON® 0-ring 4 and pump chamber 2a and TEFLON® 0-ring 4 and SMA membrane 3 are watertight. A small cavity 9 is formed between the membrane seat surface 25 and the SMA membrane 3. The retaining lid 1 and pump chamber 2a are electrically insulated.

[0022] The membrane seat surface 25 is preferably dome-shaped and has the inlet 5 located in at the top of the dome and the outlets 6 located equidistantly around the outer perimeter of the domed surface. The inlet 7 in the actuator body is joined to inlet 5 to provide fluid flow into the actuation chamber. The fluid introduced through inlet 5 is at a temperature that is below the martensite-austenite transition temperature of the given membrane material and it is introduced at a bias force or pressure that is sufficient to move the membrane from its undistorted form (adjacent to the domed seat) to a distorted form where the membrane is displaced away from the domed-seat 25. Upon heating to a temperature above its martensite-austenite transition temperature, the membrane seeks to return to its original undistorted shape. This exerts the necessary force or pressure to move the fluid in the cavity between the membrane 3 and the domed-seat 25 out of the actuation chamber through outlets 6.

[0023] The membrane 3 may be viewed as having an active side that is adjacent to the domed-seat 25 and an inactive side. The membrane 3 divides the actuation chamber into a pump chamber 9 (see FIG. 2) located between the membrane 3 and the domed-seat surface 25 and an idle chamber located between the inactive side of the membrane 3 and the lid 1. The volume of the pump chamber increases (and the volume of the idle chamber decreases) when the membrane is moved from it undistorted form to its distorted form upon application of bias pressure when the membrane is below its martensite-austenite transition temperature. Upon heating of the distorted membrane, the membrane moves back to its undistorted form with sufficient force to overcome the bias force and move liquid out of the pump chamber. Relatively cool liquid (at least below the martensite-austenite transition

temperature for the membrane) is again introduced under bias pressure to cool the membrane so that it can be distorted again once the membrane falls below its martensite-austenite transition temperature. The flow of fluid provided by the inlet-outlet configuration in the domed seat surface provides for effective convective cooling of the membrane to allow more rapid pumping cycles.

[0024] In order to prevent fluid from exiting the inlet 5 during high pressure operation (movement of heated membrane from its distorted form to its undistorted form) a flow control mechanism, such as a check valve (not shown) is provided insure one-way fluid flow at that inlet port 5 into the pump chamber. An outlet port 10 (FIG. 4) is connected to the outlets 6 by an appropriate manifold to provide removal the fluid from the pump chamber and actuator body 2a. The outlet port 10 also includes some type of flow control mechanism to insure that fluid does not flow back into the pump chamber when the membrane is under the lower bias pressure or force. Exemplary outlet flow control mechanisms may include a check valve (not shown) to prevent reverse fluid flow from the outlet back into the pump chamber.

[0025] Referring now to FIG. 2, cool liquid (at least below the martensite-austenite transition temperature for the membrane) enters through inlet 7 (see FIGS. 1 and 4) and exits the actuator body 2a through inlet porthole 5 in the domed membrane seat 25 such that the liquid impinges on a hot SMA membrane 3. The heated liquid exits the pump chamber 9 through exit portholes 6 and exits the actuator body 2a through an outlet 10 (see FIG. 4). As mentioned previously, the outlet 10 is connected to a check valve such that the liquid flows in a single direction out of the actuator body 2a. This fluid flow configuration over the membrane provides effective convective cooling of the membrane to a temperature below the martensite-austenite transition temperature at which point the bias pressure is again used to move the membrane from its undistorted form to a distorted form.

[0026] When charge is applied to the SMA membrane 3 to provide heating to a temperature above the martensite-austenite transition temperature, the deformation of membrane 3 decreases such that the radius of curvature 11 decreases (see FIG. 3). The radius of curvature 11 decreases with a force that is enough to overcome bias pressure applied in the pumping chamber 2a. The decrease in radius of curvature 11 also increases internal pressure within the pumping chamber 2a and forces liquid to outlet 10. The liquid is forced out of the check valve, which is adjoined to outlet 10

and exerts pressure to operate a piston located in a cylinder or other actuation device or simply to pump the liquid from one location to another. The internal pressure within the pump chamber 9 decreases as liquid leaves the pump chamber 9. When charge is not applied to the SMA membrane 3, the bias pressure forces cool liquid to enter the pumping chamber through inlet 7. The bias pressure causes the radius of curvature 11 of the cooled membrane 3 to increase.

[0027] FIG. 5 illustrates an embodiment with multiple membranes used in parallel to increase the volume flow rate of the system. Consider a cube or box shaped pumping chamber having six sides. The present invention contemplates any number of membranes from 1 to six to be used with the present invention. FIG. 5 illustrates a four-membrane configuration. Charge is applied to the membranes to heat them simultaneously or alternately to multiply the pumping capacity of the device. As shown in FIG. 5, four SMA membranes 3 are assembled at each domed membrane seat face of the actuator body 2b to allow parallel pumping of liquid. A check valve adjoins inlet 7 such that liquid flows in a single direction into the actuator body 2b. Cool liquid enters the actuator body 2b through inlet 7 and simultaneously enters four pump chambers 9 through four inlet portholes 5 such that liquid impinges on hot the four SMA membranes 3. Heated liquid leaves the individual pump chambers 9 through outlet portholes 6. Liquid leaves the actuator body 2b through outlet 10 which is connected to the portholes 6 by way of an appropriate outlet manifold configuration (not shown). A check valve adjoins outlet 10 such that liquid flows in a single direction out of the actuator body 2b.

[0028] FIG. 6 is a perspective view of a membrane for use in one embodiment of the invention. In the example shown, the membrane has a thickness of 5 micrometers and dimensions of 17 mm wide and 17 mm long. The membrane need not be square but may be any suitable shape without departing from the scope of the invention. The diameter of the circular area where the bias load is applied to the membrane is approximately 11 mm. A current load of approximately 21 amps is used to heat the membrane. The timing of the pump cycle is 1 cycle @ 100Hz which is equal to a pump cycle of 0.01 seconds. At this timing cycle (100 Hz), the heating time can vary from 1-10% (heating time =0.0001 to 0.001 second and cooling time = 0.9999 to 0.999 seconds).

[0029] Any of the known SMA materials may be used as the membrane material. NiTi alloys are preferred. In a preferred embodiment of the invention, the composition of the membrane is approximately 53% Titanium and approximately 47% Nickel.

[0030] Having thus described exemplary embodiments of the present invention, it should be noted by those skilled in the art that the within disclosures are exemplary only and that various other alternatives, adaptations and modifications may be made within the scope of the present invention. Accordingly, the present invention is not limited to the above preferred embodiments and examples, but is only limited by the following claims.

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